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Abstract: *Gervaise & al 2011 and Barazzutti & al 2013 described the general structure of a scheme to estimate the nature of superficial sediment in shallow waters using marine mammal's whistles and a single receiver. The multipath structure of calls given by a spectrogram is used to estimate the source characteristics and the superficial sea bottom features. A field application of this method was presented in [11] using controlled signals similar to marine mammal's vocalizations in a shallow water environment on a sandy bottom. However, contrary to the source used during that experiment, marine mammals are directive sources and the directivity loss underwent by the multipath must be taken into account in our inversion process. Indeed, the directivity is a function of frequency and emission angle (sound-source azimuth), and impacts each path differently. Thus the bottom path, once corrected from transmission loss, must be corrected from directivity loss before being used to estimate the bottom features. The emission angle can easily be geometrically related to the arrival angle and a specific unknown angle we called attitude (source orientation in space during the emission). However, the directivity patterns of marine mammals are not well studied yet, especially for vocalizations (e.g. directivity model assumption – Au 1993[4], directivity pattern measurement – Au & al 2012[9], etc.) and contrary to other mammals the unknown "attitude" parameter is not that easy to observe (e.g. Dantzker & al 1999). Our communication aims at describing different methods to estimate the "attitude" angle and the directivity loss for marine mammals. Their performances and limits are evaluated using simulated data.*

Keywords: *Directivity, Inversion, Geoacoustic, Marine Mammals*

1. INTRODUCTION AND CONTEXT

Directivity both on land and undersea – In mentioned emission beam pattern studies ([1] to [9]), authors aim at finding satisfying models to understand the emission pattern observations. For nasally emitting bat for instance, sound emission through the nostrils can be approached by two emitters close enough to interfere and act on the beam directivity, with evidences of a relation between the nostrils separation and the emitted wavelength [1]. For orally emitting bat, [2] demonstrate the relation between the mouth radius and the radius of the circular piston model. Nonetheless, they show that, the piston model explains the directivity direction but not the whole beam pattern, especially the ventral side lobe observed for different species of bats [2, 3]. Undersea, [4] assumes also the model of a circular piston on an infinite baffle as the directivity index model for marine mammals. They give values of the radius for Atlantic bottlenose dolphins (*Tursiops truncatus*) or Belugas (*Delphinapterus leucas*). [5] measure some false killer whale (*Pseudorca crassidens*) transmission pattern and reveal its directivity index can be modelled by a planar rectangular transducer. The male sage grouse (*Centrocercus Urophasianus*) acoustic emission is highly directive and enables the male to attract females with high-intensity signals while showing them all the same its best profile. The beam pattern of male sage grouse whistles beam pattern is asymmetric about the bird's anterior-posterior axis and presents a null directivity in front of the bird (contrary to the common beam pattern which main axis quite matches the head orientation **-** [6]).

All these studies use captive animals or, at least, animals with assessable position, attitude (pitch) and yaw. Indeed [6] study free-flying birds but use video records to assess the position and attitude. [5] and [7] use supervised configurations where the source is trained to take a specific position. This implies the [source - receivers] geometry and main axis orientation are known. What is more, the emissions are often stimulated, electrically for bats ([2], [8]), or with trained exercises for marine mammals ([5], [9], [7]).

Context of our work – The directivity pattern is not the purpose of our work but a mean to access the information we need. [10] and [11] describe the general structure of a scheme to estimate the nature of superficial sediment in shallow waters using marine mammal's whistles and a single receiver. The multipath structure and levels of calls resolved by spectrogram are used to estimate the source characteristics and the superficial sea bottom features. As marine mammals are directive sources, these levels have to be corrected from directivity losses. Moreover, in our situation, we use free-swimming sources so that we do not have direct access to the [source - receiver] geometry nor to the emitted signal. The location of the source is estimated using multipath arrivals. The attitude of the source is missing. Furthermore, we work with a single hydrophone. Thus, for one whistle, we get few emission angles (those from the multipath structures). The visibility on the beam pattern remains therefore partial.

Content – In this paper, we present briefly the inversion scheme. Then we detail the directivity issue for our inversion scheme and we describe the different methods considered and to be considered.

2. DIRECTIVITY

2.1. Observations

Most of the studies presented deal with clicks and pulses and rarely with whistles ([7], [6]).

We perform three sessions of acoustic records in 2009 and 2010 in Bay of Biscay and Ushant area. Autonomous recorders AURAL from Multi Electronic Inc. were moored in shallow water (130 m) at 85 m depth. An exhaustive exploration of these data with a home-made whistles detector indicates that the 2009's record present nine hours filled with whistles on a total of 52 hours of measurements, where 9 were covered by dolphins (*Delphinus Delphi*) signals.

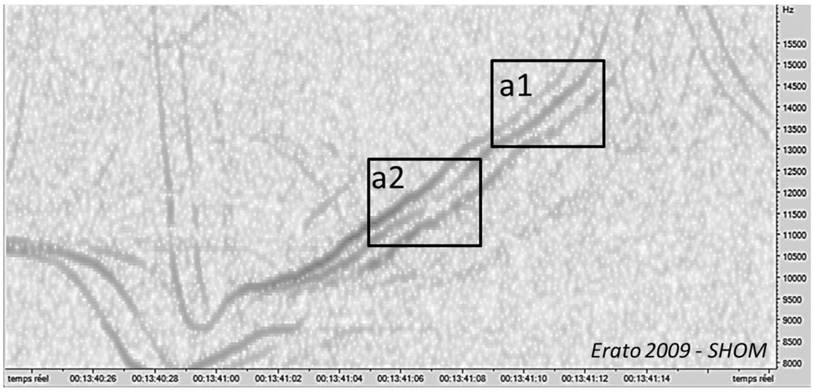

Fig. 1 - Whistle from Bay of Biscay recording. Box a1: the second path level is higher than the direct one. Box a2: quite null level.

Hundred whistles have been processed using the first step of the inversion scheme: source localization, integrated level of the first paths. From this evaluation, we learnt about our method (functioning domain (for source-receivers optimal configurations), selected signal features) and about the acoustic behaviour of the met dolphins.

Fig. 1 shows a whistle that carries proofs of directivity. In box a1, the second path level cannot be higher than the direct one since it travelled a longer distance. In a2, the presence of nulls for some frequencies reflects the different attenuations according to the frequency in the path emission direction. Table 1 gives statistics that highlight the directivity of the dolphin whistles.

Differences between the broadband level of the direct path and the first reflected path (without transmission loss correction)				
Mean	**Standard deviation**	**Quartiles**		
		25 %	**50 %**	**75 %**
-0.2364	7.2136	-4.8344	-0.8984	2.4943

Table 1 - Some statistics extracted from the 100 whistles study

2.2. First method to access directivity features: use of the commonly admitted model

The circular piston in an infinite baffle is a simple model for directional acoustic emission.

$$I = I_0[\frac{2J_1(a\,2\pi f/c\,\sin(\theta))}{a\,2\pi f/c\,\sin(\theta)}] \tag{1}$$

where I_0 is the intensity on the main axis, a the piston radius, f the frequency, c the sound speed, θ the angle with the normal to the piston surface, J_1 the first-order Bessel function. [4] explains that the acoustic projection system of the dolphin can be modeled by an equivalent piston with the same directivity index and the same near-field/far-field transition distance.

In the path level correction step, the directivity model features are learnt from the direct and first surface reflected paths, both not impacted by the bottom features. Both the attitude of the source and the piston radius (which we consider individual-specific) were estimated. We used the observed level differences between the surface and the direct path as observable and a mean least square optimization ([12]).

Equations (2) and (3) give respectively the measurements and the estimate used in the optimization step.

$$measure = 10.log_{10}|SL.H_s + N|^2 - 10.log_{10}(|SL.H_d + N|^2) \tag{2}$$

$$estimate = 10.log_{10}\left|\frac{2.J_1(p.2\pi.\frac{f}{c}.\sin(\alpha-\theta_d))}{p.2\pi.\frac{f}{c}.\sin(\alpha-\theta_d)}\right|^2 - 10.log_{10}\left|\frac{2.J_1(p.2\pi.\frac{f}{c}.\sin(-\alpha-\theta_s))}{p.2\pi.\frac{f}{c}.\sin(-\alpha-\theta_s)}\right|^2 \tag{3}$$

Cramer-Rao studies highlight the performances of this model. With both the radius and attitude estimated, bad performances occur in specific predictable directions. Monte-Carlo simulations on synthetic data confirmed this observation ([12]).

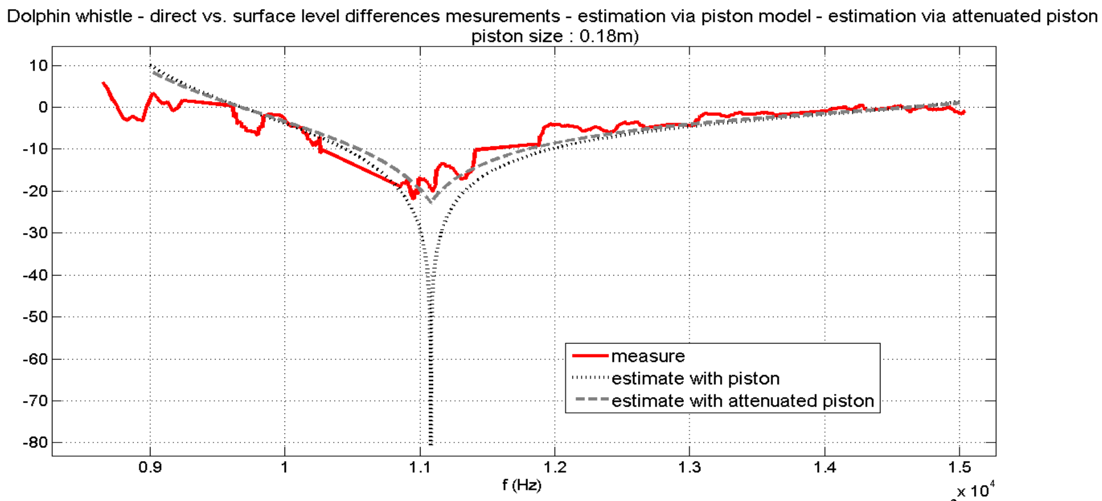

Fig. 2 - Real data observations compared to the classical and attenuated (Cte=10^{-2}) piston model

As also observed in [4], [9] and [7], even if the circular piston is a rather good model to explain the directivity index of the dolphin transmission beam, it does not well describe the off-axis shape of the transmission beam pattern. We tried to bypass this observation, including an attenuation constant in the formula to take into account both the ambient noise level and the fact that no sharp nulls are encounter in real dolphin signals.

$$H(\theta) + Cte.\left(1 - H(\theta)\right) \quad with \quad H(\theta) = \frac{2.J_1(p.2\pi.\frac{f}{c}.\sin(\theta))}{p.2\pi.\frac{f}{c}.\sin(\theta)} \tag{4}$$

With *Cte* a constant evaluated using the noise to signal ratio. This attenuated model showed a better fit to the data but it keeps limitations such as the only 2D view, a symmetry jaw/melon which contradicts the Tursiops beam pattern measurements ([4]).

Fig. 2 shows one result with the piston and attenuated piston models. The piston radii we got were rather high compared to the literature (0.18 m against 0.04 in [4]) and the differences between the model and the observation were too important to use the approximate model to correct the bottom path from directivity losses.

2.3. Second hint: design and estimation at the same time

[13] presents methods to design an arbitrary beam former response. The general solution to wave equation, driving the beamforming, can be decomposed into modes. The solution can be expressed as a sum of modes of spherical harmonics (see equation (5)).

$$b(r,\theta,\varphi;k) = \sum_{n=0}^{\infty}\sum_{m=-n}^{n} \alpha_{nm}(k) h_n^{(1)}(kr) Y_{nm}(\theta,\varphi) \tag{5}$$

with $\alpha_{nm}(k)$ a set of frequency dependent modal coefficient, $k=2\pi f/c$, $h_n^{(1)}$the spherical hankel function of the first kind, Y_{nm} spherical harmonics operating Legendre polynomials. The analysis equation (projection of (5) on spherical harmonics base) gives the $\alpha_{nm}(k)$ coefficients for an arbitrary beam pattern. *E.g.* a piston diagram can be built using 4 modes (for less than 5% of relative error), see Fig. 3.

We dispose, for each whistle, of the level differences between the surface path and the direct path, for different frequencies as shown in equation (2). Using n_w whistles and n_f frequency bandwidths centered on f_{ci} (i=1..10), we have $n_w \times n_f$ measurements. In (3), we replace the piston model by the spherical harmonics model (5). We are looking for n_w attitudes (pitch or elevation angles) and n_w yaw (or heading) angles. Considering only one common pattern for all the sources, we have to estimate $\sum_{n=0..N}(2n+1)$ coefficients with N the number of modes chosen to approximate the pattern. For 4 modes and 100 whistles, we are searching for 225 unknown with 1000 measurements. With some assumptions (e.g. symmetry), the number of coefficients can be reduced.

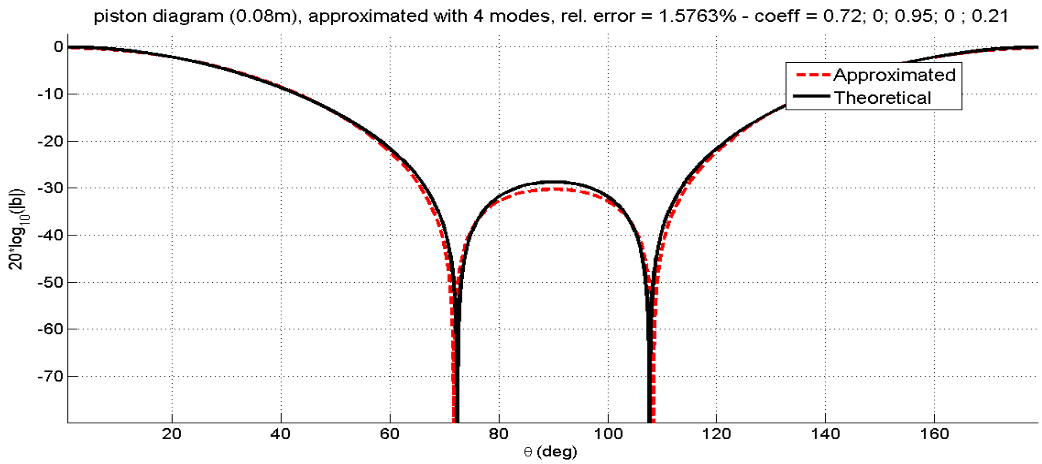

Fig. 3 - Piston diagram approximation by spherical harmonics – 4 modes for a 8 cm radius

A global optimization method can be applied to estimate the set of coefficients of the pattern and the angles characterizing the directivity.

3. DISCUSSION AND PERSPECTIVES

The piston model has been evaluated but did not give satisfaction because it creates nulls that are not realistic and even with the best parameters, the bottom level correction will be compromised by this. The second method is still in progress but seems to offer more flexibility to model asymmetry and to access and correct from directivity. The conditioning study of the model shows how sensitive the model is to the coefficients and angles errors.

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